Active Sample Acquisition System for Micro-Penetrators

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Abstract

This paper summarizes the design and development of a sub-surface sample acquisition system for use in micro-penetrators. The system was developed for flight use under NASA's New Millennium Program, Deep Space 2 project. The system's goal is to acquire approximately 100 mg of Martian sub-surface soil and return it to the inside of the micro-penetrator for analysis to determine the presence of water. Various passive and active sampling techniques that were tested during the development cycle are described. After significant testing, a side bore drill mechanism was chosen to be developed for use in the flight penetrators. The design, development, and testing of each of this mechanism's elements are outlined, with particular emphasis placed on actuator development, drill stem design, impact testing, and mechanism testing in various soil types. The system's other elements, a pyrotechnically actuated door mechanism to seal the sample and an impact restraint mechanism, are also described.

Introduction

The goal of obtaining a sub-surface soil sample is widely regarded in the scientific community as critical to unlocking the mysteries of the Martian past. This is because, planetary scientists argue, most of the evidence of the planet's geologic history is obscured on the surface by a layer of younger material - dust that has been distributed relatively uniformly around the planet. In order to reach conclusions about Mars' past, a sample of material must be obtained undisturbed from beneath the surface. One of the most straight-forward methods of getting to this sub-surface material is through the use of a soil penetrator, a simple device that uses its own kinetic energy to bury itself upon impact with the surface. This type of spacecraft is currently being developed as a part of NASA's New Millennium Program, which is managed by the Jet Propulsion Laboratory. The program's goal is the flight demonstration and validation of new technologies and techniques needed for the next century's robotic explorers [1]. The second of these missions, Deep Space 2 (DS-2), or Mars Microprobe, will deliver two micro-penetrators to the surface of Mars. Scheduled for launch in January of 1999, the basketball-sized crafts will piggy-back to Mars onboard the Mars Surveyor '98 Lander cruise stage. The probes consist of three major parts: aeroshell, forebody, and aftbody. The aeroshell protects and orients the rest of the probe during entry into the Martian atmosphere. Instead of separating from the rest of the craft, the aeroshell stays

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attached to the rest of the probe until impact. The aeroshell is made of a brittle ceramic material which allows the probe to punch through when it reaches the surface. Upon impact at an estimated velocity of 200 m/s, the probe separates into two main sections, shown in Figure 1. The aftbody stays on the surface, housing batteries and telecommunications assemblies for transmission to the Mars Global Surveyor spacecraft. The bullet shaped forebody penetrates and descends into the sub-surface, containing the sample acquisition system and science experiment. The forebody and aftbody remain connected through a flex umbilical that provides power to the forebody and data transfer to the aftbody for communication to Earth. Once a sample has been collected, it is sealed in a ceramic chamber and heated. Any water vapor that is created is evacuated through small holes in the bottom of the chamber and into an analysis chamber, where a tunable diode laser detects the water vapor. The data is then transmitted along with temperature and pressure information, which will be collected throughout the 14 day mission length [2]. The remainder of this paper describes the design, development, and testing of the system used on DS-2 to acquire the sub-surface sample, starting first with a discussion of the various sampling techniques tested, as well as the reasons for the selection of the technique used on DS-2.

Sampling Techniques

In using a micro-penetrator as the platform, several techniques can be implemented to acquire a sub-surface soil sample. These techniques can be separated into two broad categories: passive and active. Passive systems simply use the kinetic energy of the penetrator impact itself and/or gravity to collect the sample. This approach is desirable since the sample is collected without the addition of another mechanism, making the system more robust. Active systems wait until after impact and penetration has occurred and use an additional action to obtain the soil sample. This avenue is not as desirable as the passive technique, since additional complexity must be added to the probe in order to accomplish the task.

To experiment with various passive and active concepts, prototypes of each technique were fabricated and impact tested. Penetrator testing was carried out in an air gun owned by Sandia National Labs and operated by the New Mexico Institute of Mining and Technology's Energetic Materials Research and Test Center (EMRTC) [3]. Each of the prototypes was fired into a clay and/or sand matrix target which was coated with colored chalk so that surface material was discernible. Passive sampling techniques included: a rear sampler, where the soil sample was collected from material that fell into the back of the probe; a side sampler, where the sample fell into twelve holes angled 45 degrees off of vertical; a digestive tract sampler, where the sample passes through a tapered hole along the penetration axis of the forebody. As explained in [3], the results of the passive acquisition tests were unfavorable. In each case, surface soil was found mixed in with the rest of the sample, indicating that the sample did not wholly originate from the final rest position of the forebody. It was also impossible to determine from what depth the rest of the sample had been taken. In addition, a boundary layer of surface material averaging 1mm thick was seen to surround the outside surface of the forebody. This boundary layer would have to be cleared in order to reach uncontaminated sub-surface soil. In light of this information, it was decided that an active sampling technique would have to be employed in order to accurately obtain a sub-surface sample. After initial testing, a compact drill mechanism seemed the most viable option. In addition, the drill axis could be oriented to drill out the side of the forebody, where the surface contamination would be minimized.

The DS-2 Drill Mechanism

For DS-2, an active side bore drill mechanism was selected as the baseline configuration for flight. The mechanism consists of three sub-components: drill tip/auger, torque/axial force transfer, and drill motor. To capture a sample, the mechanism drills out the side of the forebody. Material is then transported back into the forebody by means of the auger flutes. The collected soil then falls through a 7 mm hole into the sample chamber. A pyrotechnically activated door mechanism then closes over the sample, sealing it from the rest of the forebody. The sample is then heated and analyzed for the presence of water.

The constraints and design criteria that the mechanism needed to fulfill were significant. The forebody's internal cavity, where the mechanism must reside, is a cylinder measuring only 36 mm in diameter by 83.5 mm in length. Along with the mechanism, the volume must also contain the probe's microcontroller and electronics, water detection experiment and electronics, temperature sensors, impact accelerometer, flex umbilical connecting forebody to aftbody, heating chamber, and a chamber door mechanism to isolate the collected sample. In addition to the significant packaging challenges, the mechanism also faced considerable environmental and performance issues. First, the probe's impact velocity is estimated to be 200 m/s. This corresponds to a worst case loading of the forebody of 30,000 G's axially. The variance in angle of attack and angle of incidence of the probe creates the possibility of a worst case lateral load of 15,000 G's in the forebody. Second, the mechanism must survive impact at a temperature of -40 °C. Third, the mechanism must operate several hours after impact, which gives the forebody time to cool down to sub-surface temperatures. Because of this, a worst case operating temperature of -125 °C at a pressure of .8 kPa (6 torr) CO_2 was imposed on the mechanism. Fourth, because the probe must use on-board power sparingly, the mechanism was allotted only 5 minutes to obtain the required 100 mg of sub-surface soil. Fifth, the mechanism must be able to keep itself closed during launch, cruise and impact, and open itself up during sample collection. This requirement keeps the drill mechanism isolated and free of surface contamination caused by soil entering the sample collection chamber simply by the force of impact. The mechanism then opens itself when ready to collect a sample. Sixth, the stroke of the drill must be great enough to extend past the boundary layer of surface soil surrounding the forebody and far enough into the undisturbed sub-surface soil that a good sample can be taken. Seventh, the characteristics of the soil to be drilled are unknown. Because of the limited knowledge about the nature of the impact area, the soil encountered upon impact could be anything from dry sand to solid ice. An exploded view of drill mechanism elements is shown in Figure 2. A cross-sectional view of the forebody, showing drill mechanism elements, is shown in Figure 3. In the sections that follow, the design and development of the mechanism's sub-assemblies will be discussed.

Drill Tip/Auger

The drill tip/auger sub-assembly of the mechanism needed to be one of the most robust. Because of the wide variety of soils possible at the impact site, the drill tip/auger must be designed to drill through the strongest soils while still being able to transport the weakest, most granular media. In addition, the design was driven to a two-part configuration because of the desire for the mechanism to be self closing.

The drilling of frozen media is of considerable terrestrial importance. Oil and well drilling, in addition to mining applications, must understand how the properties of frozen ground will affect the ability to penetrate and transport the media. Unfortunately, frozen soil properties are not homogeneous, and vary wildly with water content. At one extreme, dry frozen soil has no shear strength whatsoever and can be quite difficult to transport in the flutes of a drill. At the other extreme, saturated frozen soil is analogous to rock, with relatively high strength in shear, and can be quite difficult to penetrate [4]. In many terrestrial applications, brute force is used to solve penetration difficulties [5]. Of course, this was not a possibility for the DS-2 drill mechanism application. In any drilling application, three main factors affect successful drilling performance: one, having adequate available torque to continue the cutting action; two, having adequate axial force to continue penetration; and three, having the correct cutter geometry for the material being penetrated. The balance between these three factors is critical to the performance of the drill. This was no different for the DS-2 drilling application. As a starting point for the mechanism design, the torque and axial force requirements for drilling into various frozen soil samples were first determined, which was accomplished through the use of a custom test apparatus. The apparatus used compression springs to provide axial force on a conventional 9.53 mm (.375 in) high speed steel drill bit, while an Instron machine was set to spin a frozen soil sample at a constant rate of .838 rad/s (8 RPM). The drill bit was put into contact with soil and allowed to penetrate for 5 minutes. Torque and axial force levels were recorded throughout the test. The soil samples used to perform the tests were a hybrid mix of frozen sand and water at varying % H_2O by weight. The sand was a mix of grain sizes, with an nominal grain size around 150μ. The sand was saturated at 20% by weight H_2O, and this was considered to be the worst case soil sample. At worst case, an initial axial spring force of 44.5 N (10 lbf) allowed for continuous penetration. The torque required to cut the material averaged between .226 and .282 N•m (2 and 2.5 in•lbf). The average penetration into the worst case material after 5 minutes was 5.08 - 6.35 mm (.20 - .25 in).

Once the torque and force requirements were determined, the cutter geometry needed to be defined. This was accomplished through the use of another custom test apparatus, shown in Figure 4. This drill test rig allowed the user to swap in and out custom and commercial drill tips of differing diameters and cutting geometries and to vary the amount of initial axial spring force that was applied. The test rig also allowed different actuators and gear reductions to be tested. In addition, the feasibility of the sampling technique was itself tested. A 7 mm hole was bored from the bottom up into the drill bore to mimic the hole the sample would fall through to get to the sample heating chamber. Various soil samples could be placed into and removed from a square housing in the front of the test rig. Over 60 trials using various custom and commercial drill bits, coring bits, end mills, and reamers were completed, with torque and axial force data being recorded. In addition, total drill extension and sample acquired were also measured. The following general trends seemed to follow true throughout the testing: one, because the total extension of the drill during the 5 minute cycle was quite small, drills with flatter point angles tended to yield a greater sample size; two, an increase in relief angle, the angle between the cutting edge and the material, tended to increase penetration rate; three, a higher helix angle (~60 deg.) tended to provide better material transportation in both dry and saturated soils; four, because of the short operating time, larger bit sizes (~9.53mm (.375 in)) tended to more effectively acquire the required 100 mg soil sample in the allotted operating time; and five, because of the short operating time, carbide or nitride coatings did little to improve the cutting performance over standard high speed steel bits.

Using the results obtained from the drill tests, a hybrid tip and auger were created. The tip was fabricated from T1 high speed tool steel. The tip had an flat point angle, 8 degree relief angle, and a 13 degree rake. During testing, this combination of cutting angles seemed to yield the best overall cutting performance for the widest range of materials. The auger was fabricated from titanium, essentially for its high strength to weight ratio, with a 60 degree double helix material transport. This unit was then tested in various frozen soil samples. The results, shown in Table 1, show favorable performance for a wide variety of different frozen soil types.

In addition to being optimized to drill into frozen soil, the drill tip/auger sub-assembly is also designed to shutter itself open and closed. This feature allows the drill mechanism to remain closed during impact and the open up during the first few degrees of rotation upon start of the drilling sequence. This is accomplished by designing the drill tip with two pockets machined in its back face. These pockets accept mating nubs on the front face of the auger. The shaft of the drill tip also runs down a mating hole in the auger and is shoulder bolted at its end, permitting the drill tip to rotate but not to be moved axially. This design allows the drill tip to be shuttered open and closed on hard stops, as the nubs hit the ends of their respective pockets. A representation of this design is shown in Figure 5.

Torque/Axial Force Transfer

This sub-assembly's purpose is to provide to the drill tip/auger sub-assembly the necessary torque and axial force to successfully drill into the frozen media. The sub-assembly consists of a 2.5:1, 90 degree bevel gear set, nested compression springs, and a spline. The external spline is directly fastened to the back end of the auger, while the mating geometry is machined directly into the hub of the bevel gear. The spline uses flat tooth geometry and is fabricated out of Nitronic 60, taking advantage of the alloy's anti-galling characteristics. Two compression springs in parallel provide the 44.5 N (10 lbf) of initial axial force required for drilling. The springs are nested together and housed in a cavity in the hub of the bevel gear.

The 90 degree bevel gear set is designed under an interesting set of constraints and criteria. First, the bevel gear itself is the keystone of the entire drill assembly. Its structure must support the impact loads of the auger/drill tip sub-assembly, the spline, the compression springs, as well as itself. Under a combined 30,000 G axial load and a 15,000 G lateral load, the forces on the bevel gear structure could become severe. Therefore, the bevel gear is fabricated from titanium, which gives it high strength characteristics while its relative low mass (~ 2g) lessens the overall impact load. The pinion's primary design characteristic is its own mass. As can be seen in Figure 3, the pinion resides directly in line with the motor shaft. On impact, the load of the pinion is offset from the motor shaft by means of a small ball bearing, residing directly below the pinion. However, if the impact load of the mass of the pinion is too great, significant Brinell damage of the bearing could occur. Because of this, the pinion's mass had to be minimized. Therefore, the pinion is fabricated from Aluminum 7075-T6. This ensures that the pinion can support stall loading of the geartrain while imparting as little impact load into its ball bearing as possible.

Another problem is created by the selection of these two gear materials. Titanium and aluminum are both materials that are highly susceptible to galling and cold welding in a vacuum. There is considerable risk to mechanism performance if there is no barrier between the two materials. A solid film lubricant, Lub-Lok 4306 is therefore employed to act as a barrier material between the two materials. As an added safety, the aluminum pinion is also hard anodized. The combination of these two barrier materials, in addition to the low number of cycles (~100 for pinion, 40 for gear) ensures successful operation of the mechanism.

Figure 6 shows the drill stem assembly. This assembly packages the drill tip/auger and torque/axial force transfer sub-assemblies into one assembly that can be inserted directly into the forebody. The drill stem assembly also includes an integral ball thrust bearing that the bevel gear rides on during operation. The bearing consists of ~30 Delrin 100 balls 1.59 mm (.063 in) in diameter riding in their own grooved retainer. There is a .127 mm (.005 in) nominal riding clearance between the bevel gear and the retainer. Upon impact, the balls elastically deform until the bevel gear hard stops against the retainer. This allows the impact load to be taken through the retainer and not the balls, which are unable to support a dynamic loading of that level. As can be seen in Figure 6, a restraint nut is used to keep the assembly together during launch, cruise, and impact. Upon operation of the drill mechanism, the auger turns itself out of the restraint nut in the first three rotations.

Drill Motor

The workhorse of the DS-2 drill mechanism is the drill motor, providing the necessary torque to drill into the frozen soil. As shown in Figure 3, the motor is mounted down the axis of the forebody, nested inside of the probe's electronics. The motor in and of itself presents a full set of design constraints and criteria. The motor must operate at worst case Mars temperature and pressure, -125 °C and .8 kPa (6 torr) CO_2, respectively. In addition, the orientation of the motor is such that it takes the full force of the axial impact load. The motor must also be able to provide the necessary .113 N•m (1 in•lbf) of torque required to drill the worst case saturated frozen soil. One positive design criteria, however, was that the motor had a one time operating length of only 5 minutes.

It was decided early on in the mechanism development cycle that a stock motor would be used and modified if necessary to work under the above conditions. A 10 mm Micro-Mo DC brushed motor was selected as the baseline design. The motor also included a 5 stage, 1024:1 planetary gear reduction and precious metal brushes. The motor was of a coreless rotor design.

Initial impact testing of the stock motor and gearhead revealed significant problems in its impact survivability. First, the rotor coil of the motor was pulling away from the commutator plate, causing an open in the motor circuit. This problem was remedied with the addition of a cyanoacrylate adhesive to strengthen the interface. Second, the magnet post, while successfully impacted at ambient temperatures, was failing when impacted at the expected Mars impact temperature of -40 °C. This problem was due to a brittle transformation occurring in the polyamide that the post was fabricated from. To solve the problem, the plastic post was replaced with a titanium one, greatly increasing overall strength with no undesirable temperature effects. Third, the magnet itself was shattering on impact. The stock magnet was Samarium Cobalt, a highly brittle magnet material. This magnet was replaced with a Neodymium Iron Boron (NdFeB) magnet of similar magnetic field strength. The NdFeB magnet was a much more rugged magnet material, and survived subsequent impact tests with no deleterious effects. Fourth, the magnet was found to slip on the magnet post, causing interference between the rotor and the magnet. This problem was remedied by bonding the magnet to the magnet post using EA9309 structural epoxy.

In addition to problems encountered due to impact, temperature concerns also caused modifications to be made to the stock motor and gearhead. First, the motor was shipped with sintered bronze bushings, which seized during initial tests at approximately -50 °C. The bushings were replaced with unlubricated ball bearings, which ran favorably at -125 °C. Second, the lubrication on the brushes caused them to lift away from contact with the commutator at -125 °C, which resulted in an open circuit. The lubrication was removed from the commutator and brushes to remedy this problem. Lubrication was also removed from the ball bearings and planetary geartrain of the gearhead. The planetary gears were then lubricated with finely ground MoS_2 powder. Once the gearhead's lubrication was removed, additional play was found between each of the planetary stages. The additional play was a cause for concern over possible recoil in the gearhead at impact. Two additional stage dividing washers were added to take up the excess play.

The majority of the modifications to the drill motor are ones that affect the overall motor life in a negative way. Removal of lubrication in both the bearings and between the commutator and brushes dramatically reduce the operating life of the motor. The granular MoS_2 solid lubricant could become abrasive and life-limiting after prolonged use. However, because of the small operation length of 5 minutes, these modifications were acceptable. Under a worst case load of .113 N•m (1 in•lbf), flight-like motors have run without substantial current increase for an average of 27 minutes. This value represents a ~5.5 to 1 life factor of safety over the nominal 5 minute operation, a significant value.

<u>Overall Mechanism Performance</u>

A fully functional drill mechanism has a nominal drilling speed of .628 to .838 rad /s (6-8 RPM) with a maximum drill extension of 9.53 mm (.375 in). The expected operating torque is .113 to .141 N•m (1 to 1.25 in•lbf) and a stall torque of .509 N•m (4.5 in•lbf). Motor operating current averages between 40 and 70 mA, with a stall current of greater than 300 mA. The mechanism has an operating time of 5 minutes at an unregulated voltage averaging ~10 V. To date, a fully functional drill mechanism has successfully completed a full mission sequence during two separate tests. The mechanism has survived impact at -40 °C. During the first test, it successfully demonstrated in-situ drilling and sample acquisition, acquiring 104 mg of soil sample from the impact target. In both tests, the forebody was removed from the target and brought back to JPL, where drilling tests were successfully completed at expected worst case Mars temperature and pressure, -125 °C and .8 kPa (6 torr) CO_2, respectively. The sequence will be tested once again in late May 1998 at EMRTC during the DS-2 System Qualification Impact Test.

Other System Elements

The DS-2 sample acquisition system includes two other elements without which a sub-surface sample could not be successfully acquired and analyzed. First, although the auger/drill tip sub-assembly allows the drill tip to shutter open and closed, it does not lock the tip into position. This is required so that launch or impact does not jar the tip open, causing surface soil contamination. This requirement is fulfilled with the drill shutter restraint mechanism. Shown in Figure 7, this mechanism consists of a pin with a hook-shaped end and a compression spring. During launch, cruise, and impact, this spring-loaded pin is nested into a mating pocket machined into the back face of the drill tip. The hook feature keeps the drill tip from rotating in one direction, while the non-back-driveable geartrain keeps the mechanism from rotating in the opposite direction. Upon operation, the drill tip turns away from the restraint. When it clears the pocket in the drill tip, it springs up and out of the way of the drill stem.

The second additional mechanism in the sample acquisition system is a pyrotechnically activated door closure mechanism. After a soil sample is successfully acquired, a miniature piston actuator is fired, pushing a titanium guillotine "door" over the top of the sample chamber, sealing the sample inside for analysis. The door is held in the open position during launch and impact through the use of two .5 mm dia. 303 CRES shear pins. These pins are sheared when the actuator is initiated. The miniature piston actuator is commercially available from Eagle Picher Industries, and measures 3.43 mm (.135 in) in diameter by 9.32 mm (.367 in) in length. The mechanism, shown in Figure 8, has been operated successfully at -125 °C and .8 kPa (6 torr) CO_2.

Conclusion

The design, development, and testing of the DS-2 sample acquisition system have been discussed. Various active and passive sampling techniques tested during development have been described, along with the rationale of the selection for flight of the side-bore drilling method. A detailed description of the DS-2 drill mechanism and its performance has been presented, and the design of the mechanism's sub-assemblies has been discussed in detail. Problems encountered through engineering tests have been outlined, and the solutions to those problems discussed. The resultant mechanism has been shown to successfully operate through a full mission sequence during two separate engineering tests. Finally, the design of related elements, the drill shutter restraint and pyrotechnically actuated door mechanism, has been presented.

Acknowledgments

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Table 1: Flight Drill Tip/Auger Test (5 min. Duration)

Soil Type	Soil Temp.	Avg. Current	Sample Collected
Loose Sand, 120 μ	-85 deg C	26 mA	104 mg
Loose Sand, 120 μ	-82 deg C	27 mA	95 mg
8% H_20, 120 μ	-75 deg C	40 mA	124 mg
8% H_20, 120 μ	-78 deg C	37 mA	116 mg
8% H_20, 120 μ	-80 deg C	42 mA	110 mg
10% H_20, 120 μ	-79 deg C	55 mA	101 mg
10% H_20, 120 μ	-82 deg C	52 mA	120 mg
12% H_20, 120 μ	-80 deg C	64 mA	113 mg
13% H_20, 120 μ	-76 deg C	62 mA	100 mg
15% H_20, 120 μ	-80 deg C	67 mA	105 mg
15% H_20, 120 μ	-74 deg C	70 mA	95 mg
20% H_20, 120 μ	-75 deg C	82 mA	80 mg
20% H_20, 120 μ	-77 deg C	80 mA	86 mg

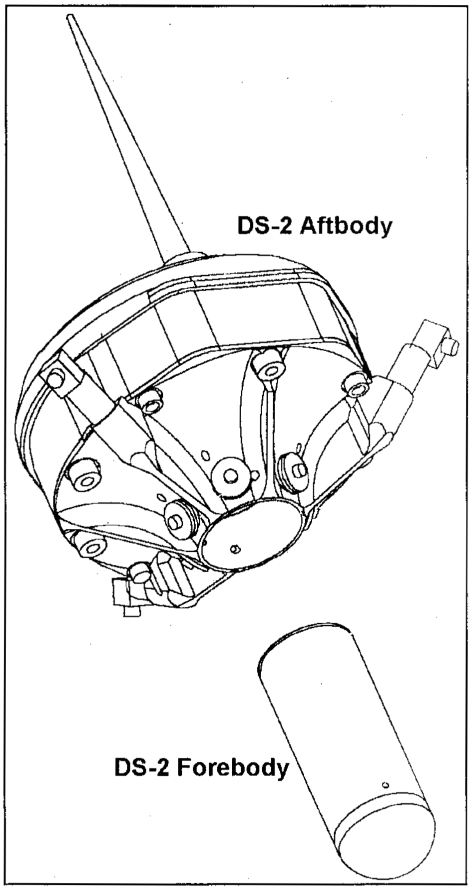

Figure 1: Deep Space 2 Forebody and Aftbody

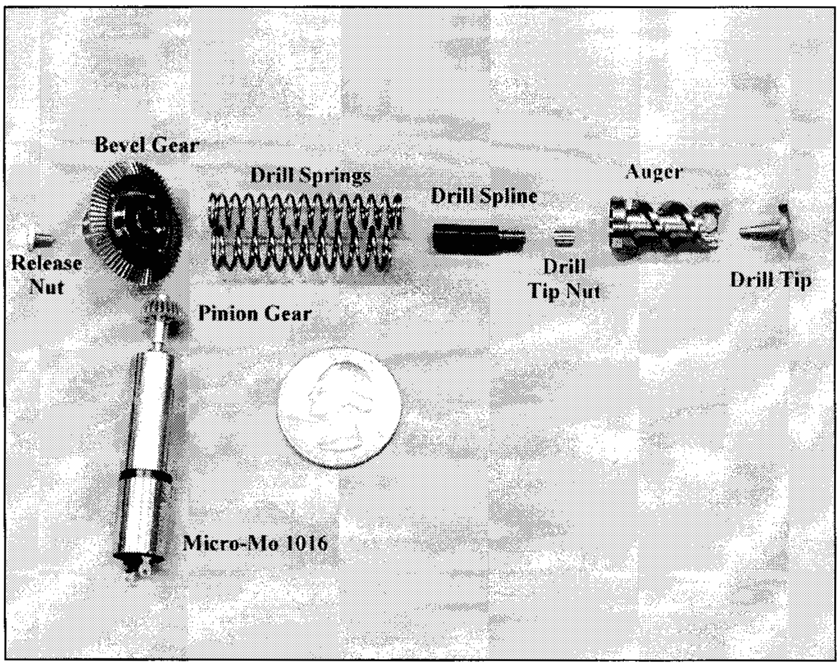

Figure 2: Exploded view of drill mechanism elements

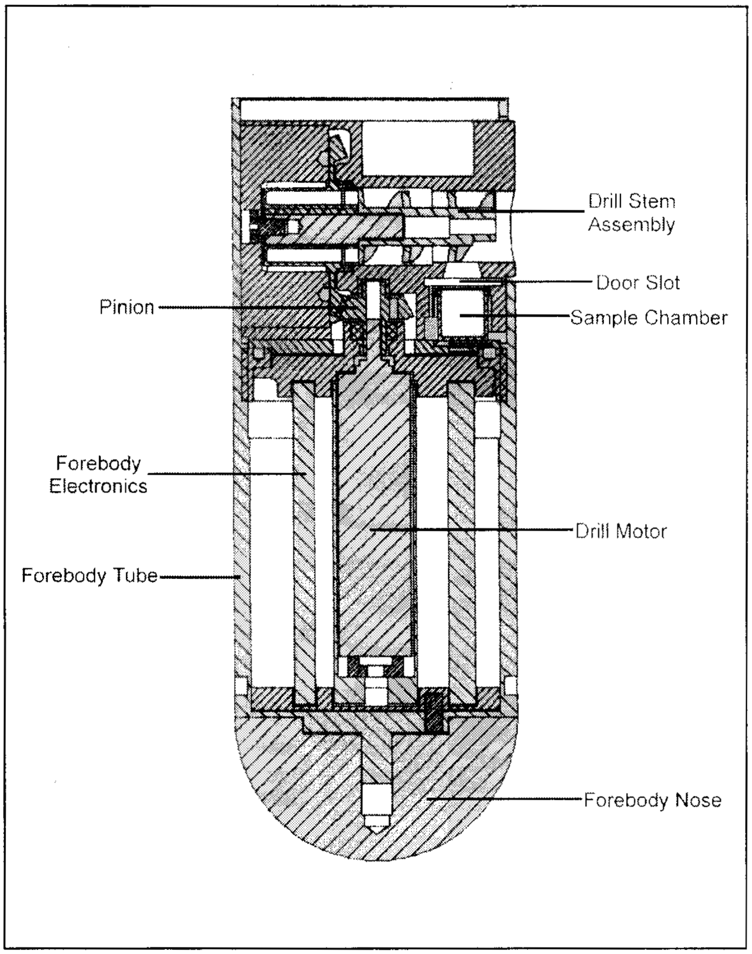

Figure 3: Cross Section of DS-2 Forebody

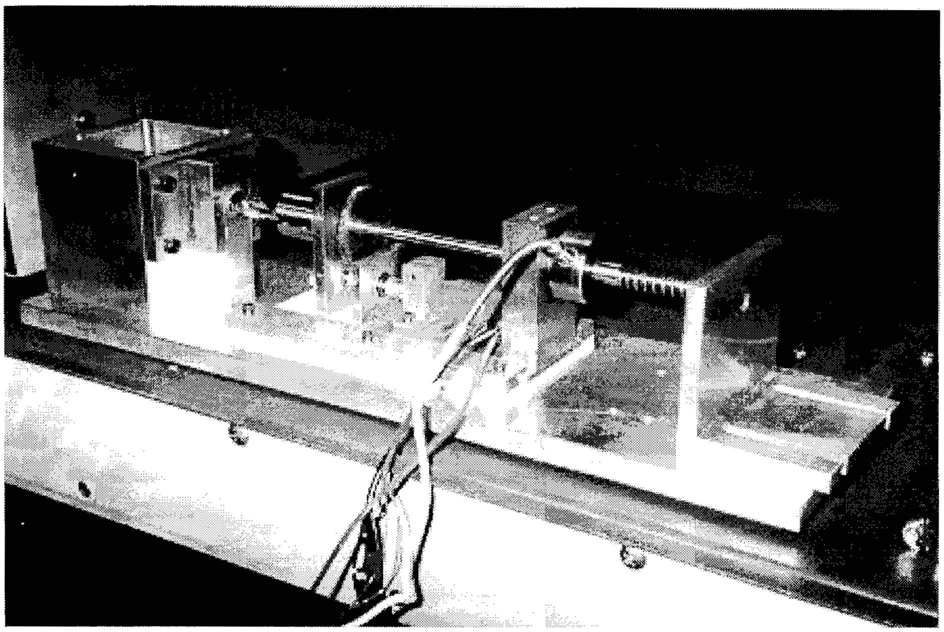

Figure 4: Drill Testing Apparatus

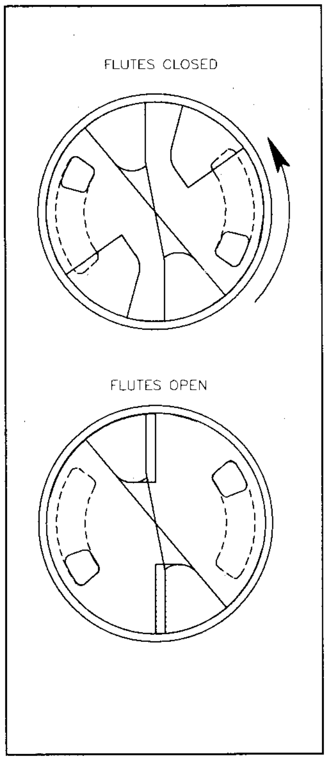

Figure 5: Auger/Drill Tip Shuttering Action

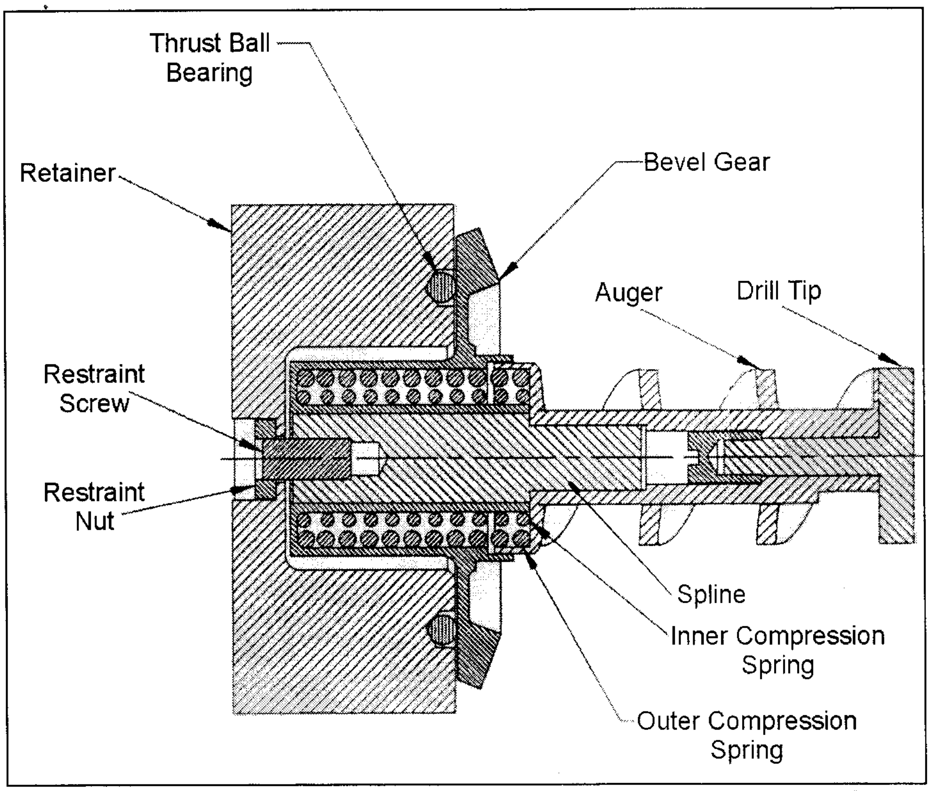

Figure 6: Cross-sectional view of Drill Stem Assembly

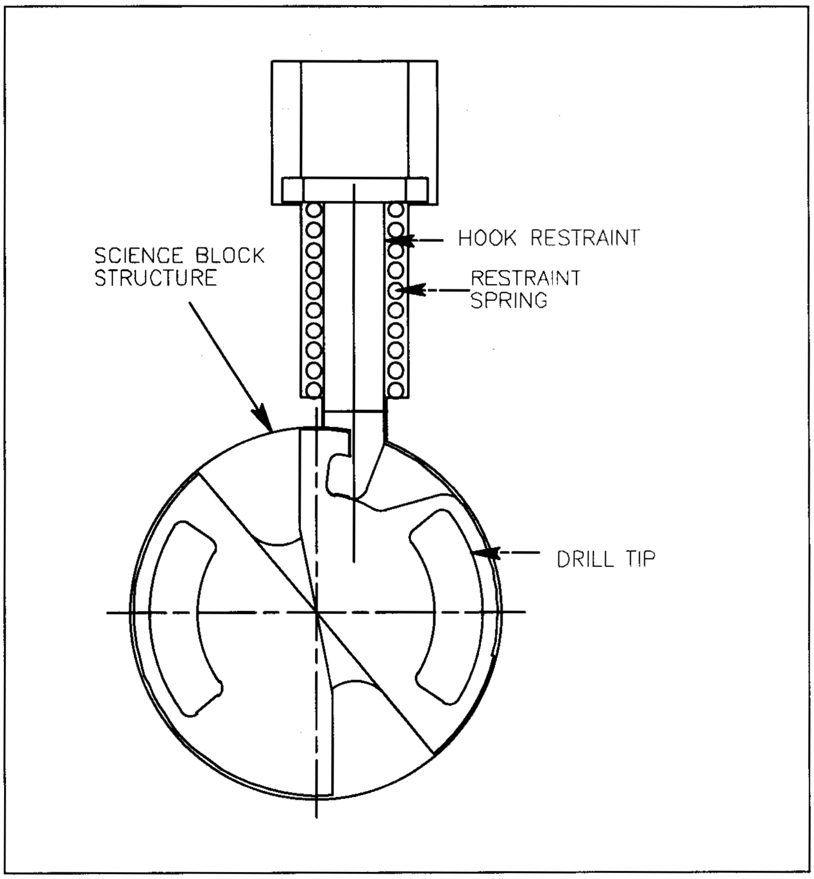

Figure 7: Drill shutter restraint mechanism

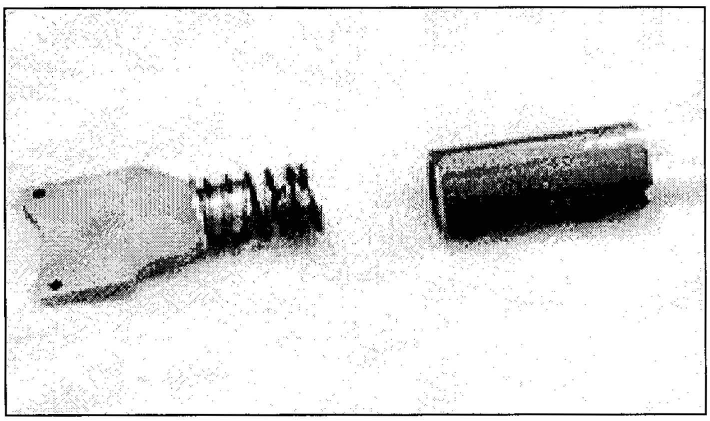

Figure 8: Pyrotechnically activated door mechanism